ALUMINUM CONDUCTORS AND CONNECTORS FOR DISTRIBUTION CIRCUITS

by

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1. The Role of Aluminum in Electrical Wires and Cables

Through its fortuitous combination of low weight and good electrical conductivity, aluminum has been considered for a long time as a good electrical conductor in aerially supported lines. By 1940 aluminum and steel reinforced aluminum conductors were being used almost exclusively for power transmission lines throughout this country.

Copper shortages resulting from World War II and the Korean conflict led to a tremendous expansion of aluminum facilities after 1948 and as a result, use of aluminum conductors in the Nation's vast distribution system was initiated and has spread rapidly. There is little doubt that this trend will grow and increase with succeeding years until aluminum will assume the dominating role. I would like to discuss some of the basic reasons for this prediction.

A. Relative Abundance of Aluminum Metal

I think it is significant to look at the records made by geologists and geophysicists, of their fairly accurate work in assessing the amount of metal and metal producing ores there are in the earth's crust and to note these figures on the basic metals that are in common use. I am sure you all have seen them before -- I'd like to repeat a few here. Relative to the data shown in Table I, one notes the following:

> The relative abundance of silicon is 26% -- top abundance, as you might expect. Aluminum, however, is in abundance of 8%, iron about half that amount at 4.1%, magnesium 1.8%, titanium surprisingly enough is .7%, copper is a poor sixth at .088%. Lead follows with 0.0019% and tin is even lower at .000136%.

B. Metals of the Future -- The Long Range Viewpoint

These figures might be rather surprising on the basis of today's quotations in various metals. However, in any long range planning or any long range use of metals, it is certain that we cannot disregard the

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TABLE I

ABUNDANCE of METALS in the EARTH'S CRUST

	Relative Abundance,%	Atomic Weight
Silicon	26	28.1
Aluminum	8	27
Iron	4.1	56
Magnesium	1.8	24.3
Titanium	.7	47.9
Copper	.088	63.6
Lead	.0019	207
Tin	.000136	118.7

abundance figures and, insofar as our material needs for bridges, machinery, vehicles, buildings, wires and cables and other hardware - aluminum, iron and magnesium will undoubtedly be the metals of the future. This seems to establish aluminum as the top long range metal for use by the electric wire and cable industry because aluminum as you know, not counting the noble metals, is second to copper only in electrical conductivity.

C. Production and Price of Aluminum in Relation to Copper

Based on the present availability, it looks as though aluminum has about twice the abundance of iron and about 800 times that of copper. It ranks second to iron today in volume of production and in growth and expansion of facilities, we are speaking of a truly phenomenal industry. In 1900 there were less than five million pounds of aluminum made. In 1951 the industry had grown to 1.67 billion pounds per year and in this year it is expected that there will be produced over three billion pounds of aluminum. The United States and Canada as you probably are aware, produce more than three quarters of the total world's supply. During this period of enormous growth in aluminum production, prices of aluminum pig have almost steadily gone down. You may be interested in some of the figures. In 1920 the price of aluminum was greater than 40¢ a pound. By 1940 it had dropped to 18.7¢. In 1951 it was at 18¢ a pound and then during the Korean war, with the emphasis on production, it rose to 20-1/2¢ a pound.

During the same period of industrial expansion, the copper production situation has not looked nearly as bright. The Bureau of Mines figures for the copper content of the ores mined in this country, either in open pit or from deep mines, show a fairly steady decline. The figures are, of course, available to everybody. In 1935 there was 1.89% of copper content in our domestic ores. By 1940 it had dropped to 1.20%; in 1945 to .93%; in 1951 to .90%. The latest tentative report that I have seen - that of last year - shows the copper content down to 0.88%. Copper pricing is an interesting but complex story and could take up a whole lecture I'm sure, by someone familiar with all its ramifications. To provide a few highlights, I can mention that copper in 1920 was at 17-1/2¢ a pound but by 1940 it had dropped to its all time low, 11.4¢ - under pressure of economic situations. During World War II copper was pegged at 11-1/2¢ and 14¢ and it was again pegged at 24-1/2¢ during the Korean conflict. In 1953 when government controls were removed, copper jumped immediately to 36-1/2¢. It's present price, dependent on how much foreign copper comes into the country and how much scrap is thrown on to the market is somewhere in the neighborhood of 30 to 30-1/2¢. However, copper prices are anything but stable and anyone that wants to talk about the price of copper has really a tough job on his hands. Based on present prices, electrolytic copper sells for 9.8¢ per cubic inch, whereas aluminum, the E.C. or electrical conductor grade, sells for 2¢ per cubic inch.

D. Consumption of Conductor Metals in Electrical Industry

The greatest consumption of copper metal is by the electrical industry and of that, electrical wires and cables take just about 51%. It is estimated that there are well over one half million conductor miles of

transmission lines built in this country. In low voltage distribution, the figures are closer to 2,500,000 conductor miles. In copper, those lines account for about two million tons; in aluminum, they would amount to less than one million tons. If the growth of overhead lines, predominantly distribution, continues at a rate of increase of only 10% per annum (which is fairly conservative) there will be required over 200,000 tons of copper per year. For aluminum, however, there will be needed only somewhere between 75 to 100,000 tons.

E. Three Factors in Choice of Aluminum

Further improved availability is likely also, in that some day we will make aluminum from the common feldspars so prevalent in all of our States by processes enabling aluminum to be made at reduced cost. This picture of the tremendous requirements for conductor metals and the giant growth trends in our electrical industry taken together with metal availability would indicate that aluminum is the metal which we will have to work with for conductor material. In reality there are three factors which control the situation:

(1) lower price per pound,

(2) fewer pounds required, and

(3) availability.

F. Is Aluminum Suitable for a Dominating Role as Conductor?

Based on the above, we must ask ourselves: Is aluminum fit for the role? Can it take over the job that has been done by copper for the past eighty years or more? Can it do the job as well? Can it do an adequate job? To those of us who are working daily with aluminum metal, the answer is an unqualified "yes". Each of the pertinent properties of aluminum can be analyzed in comparison to copper with conductor performance in mind. Based upon the how, where and what of the existing differences, one soon learns to utilize aluminum to its best advantage and so achieve a conductor for a specific purpose which performs as well as copper, in some cases with a slight advantage--in other cases with a slight disadvantage. The how, where and what of aluminum conductor design is a long story, though, and I do not propose to go into it at this meeting. You see, I was pledged to keep connectors as the major topic before us and their exposition takes a long time so we will not go into the aluminum conductor story although it is most interesting.

2. DISTRIBUTION LINE ACCESSORIES FOR ALUMINUM CONDUCTORS

A. Importance and Need for Adequate Accessories for Aluminum Conductors

Aluminum conductors have for many years found widespread use in the transmission of large blocks of electrical energy from generation points to urban centers of load. For the most part, this transmission is all at high voltage and originates at a large power (step-up) transformer and terminates at a large power (step-down) transformer. There are generally almost no tap-offs, either permanent or transient from such lines. Consequently, fittings and connectors can be and are integrally designed to exactly match the transmission line requirements with regard to service physical and electrical load impositions. The line is homogeneous from one end to the other and the best choice of clamp and connector metals can be made without introducing too many compromises.

Such has been the case in transmission line practice. Large, rugged fittings with large built in safety factors, made of the same metals as the line are the rule. No particular trouble has been experienced with such designs after they were once proven in service.

The situation with regards to distribution lines and circuits is quite different. As a rule, any new distribution circuit construction must, at one or more points, fit into some existing distribution circuit. The enormous number of distribution circuit miles (over 2,500,000 conductor miles of private and publicly owned low voltage distribution lines) together with its almost infinite complexity makes a tailor-made connector and fitting design for any individual circuit impossible both economically and technically.

In distribution circuits it is almost the rule that one conductor metal must always at some points connect with a different conductor metal. Thus: bare copper secondary circuits are often extended with aluminum triplex cable; copperweld primary distribution circuits are often extended with copper or ACSR conductors; and aluminum service drops are usually connected to copper house service entrance conductors. At all these junctions, at all the service tappings, at all the needed line splices and at all the terminations, fittings and connectors are required that are light, serviceable and inexpensive. Also, since they must be installed by distribution linemen crews at an economical rate per day, these fittings must be easy, simple and foolproof to apply. It is obvious that the fittings and philosophy of design applied to transmission line accessories are not compatible with distribution system problems.

B. Carry-overs from Copper Conductor Designs

As a result of the above, with the more or less recent introduction of substantial quantities of aluminum conductors in the distribution

field, the accessory problem became immediately acute. To meet the demand, hasty conversion of line accessories designed for copper conductors was carried out by most accessory suppliers and these products have been made available and used in large quantities. In a great many cases these fittings have not performed satisfactorily, principally because the physical characteristics of aluminum metal as used in conductors differ very appreciably from copper and the fact that a junction between these two metals posed new problems which were not anticipated.

On the other hand in a great many installations these fittings performed satisfactorily. One can say that the cases in which connectors performed satisfactorily far exceeded the cases where they did not. However, since wide usage of aluminum conductor in distribution was a new venture comparatively, troubles when they occurred were all pointed up. The promptness with which each utility and operating company indicated its troubles with connectors has been of considerable help to the industry in cases where the deficiencies showed up almost immediately. The connector people most certainly have not been asleep on the job and as a result, there are a number of designs now available which are fairly efficient. We shall see some of them shortly.

C. Difference Between Aluminum and Copper Requiring Differing Design Approach

Difficulties that arise with the use of ordinary tinned copper connectors are mostly, of course, due to differences in behavior of the metals. In Table II you can see some of these differences. The weight difference you will appreciate is fairly high -- 2.703 for aluminum and 8.89 specific gravity for copper. Melting points are quite different also -- 657°C for aluminum and 1083°C for copper. Thermal conductivity is fairly important in a conductor. We find aluminum at .520 versus .923 for copper or approximately 60% that of copper. Specific heats also differ with aluminum being considerably higher at .226 versus .092 for copper. That difference is important in short circuits and burn-off currents and it would look as though the aluminum were very favorably placed in that relation. However, since for equivalent resistance an aluminum conductor has 1.59 times as much volume as copper, the net theoretical increase in aluminum heat storage capacity amounts to only about 16%. In short circuit current heat-ups it is found that aluminum and copper actually heat at about the same rate.

The difference in elastic modulus, ten million for aluminum versus sixteen million for copper is very significant. The tensile strength differences 12,000 psi for aluminum versus 38,500 psi for copper in the annealed condition and in the fully hard condition, 27,000 psi versus 64,900 psi. Elongations of aluminum and copper are quite different in the three-quarter hard and annealed state; however, in the hard condition the two materials approach one another. I might mention that in the three-quarter hard condition, the flexibility and handling of aluminum strands are just about the same as for fully annealed copper. They both break at about the same number of bends and feel very much alike. In the fully annealed condition, aluminum appears to be very much more flexible than copper. As a result, a soft temper, stranded aluminum cable of relatively coarser stranding has the same flexibility as an annealed copper cable of, let us say, twice as many strands. Thoroughly annealed aluminum is very difficult to break by repeated bending. The Brinell hardnesses of hard drawn aluminum and copper are very different - 50 vs. 103; this plays a bearing on connector performance.

TABLE II

CHARACTERISTICS of ALUMINUM (as COMPARED to COPPER)

	EC Alum.	Electrolytic Copper
Physical & Thermal		
Specific Gravity	2.703	8.89
Melting Point °C	657	1083
Boiling Point °C	1800	2310
Thermal Conductivity, CAL/CM^2/CM/°C/SEC.	0.520	0.923
Specific Heat CAL/GR/C	.226	.092
Thermal Expansion/C	23×10^{-6}	16.4×10^{-6}
Atomic Weight	26.97	63.54
Atomic No.	13	29
Valence	3	1,2
Mechanical		
Modulus of Elasticity Lb/Sq In	10,000,000	16,000,000
Tensile Str Psi (0.1" Diam) Annealed	12,000	38,500
3/4 Hard	19,000	- - -
Hard	27,000	64,900
Elongation, %		
Annealed	40-55	30-40
3/4 Hard	5-15	- - -
Hard	1.5-2.5	1.0
Brinell Hardness (H.D. only)	50	103
Electrical		
% Conductivity (IACS-Volume Basis)		
Annealed	62-63	100
3/4 Hard	61	- - -
Hard	61	96.2
Temp. Coeff. of Resistance/°C at 20°C	0.00403	0.00393
Ratios		
Strength to weight, HD	10	7.3
3/4 HD - Annealed	7	4.3
Conductance to weight, HD	22.6	10.8
3/4 HD - Annealed	22.6	11.2

Table III summarizes what I consider to be the most important property differences between aluminum and copper as affecting connector design. The yield strength of hard drawn aluminum conductors is approximately 24,000 psi. The yield strength of copper is 40,000 lbs. The yield strength of the bronze generally used for copper connector bodies is in the order of 40,000 to 45,000 psi. This is almost in a 2 to 1 ratio with the aluminum conductor. Thermal coefficient of expansion is also an exceedingly important factor. That for aluminum is seen to be 40% greater than for copper.

The surface films that form on aluminum and copper are quite different. The aluminum oxide film which forms almost instantaneously is essentially of a dielectric nature. In heavier than normal sections its performance as a dielectric has been determined. It has a high volt per mil rating for dielectric strength which in the case of a good dense film may be 300 to 400 volts per mil. It also has a dielectric constant of about 5 and a power factor under 10%, both of which are readily measurable. It is therefore a true dielectric material and when aluminum surfaces are to be joined in electrical connections we must remove this film. On normal surfaces that are clean and have been in cool, dry storage for some time, the air formed oxide film may exist in thicknesses of about 50 to 60 angstrom units. This is still quite thin, and further film build-up under these conditions slows down remarkably. When the aluminum part is in service and exposed to the atmosphere for a long period where it may be subjected to higher temperatures and moisture, the oxide film builds up additionally and can achieve a thickness of several thousands of angstrom units.

Copper on the other hand under normal conditions produces its oxide relatively slowly. Red cuprous oxide forms first and then, as the temperature becomes higher and the exposure is prolonged, black cupric oxide is formed. Both the copper oxides are, relatively speaking semi-conductors, for example, cuprous oxide has a dielectric constant in the neighborhood of 20. Hence, these oxides have not been a real problem in the use of connectors. Best practice nevertheless is to remove the copper oxide films prior to connections. The more usual practice is simply to forget it and in truth, it has not caused a great deal of trouble.

Table III also calls our attention to the electromotive galvanic voltage between the metals using hydrogen as a base. Aluminum in an electrolyte is about 1.7 volts positive to hydrogen whereas copper is .344 volts negative. There is thus just a little over 2 volts of D.C. potential difference between copper and aluminum in solution, the aluminum being positive. A cell made up of these two metals in the presence of electrolyte, moisture, and a closed return circuit will pass current through the electrolyte and the aluminum anode will deposit its metal irreversibly into solution. Such depositions from the aluminum metal anode are in the form of oxides and hydrated oxides and these will be continuously and copiously evolved as long as the conditions persist or until there is complete destruction of the anode metal.

The factors that I have just reviewed in Table III are esentially the most important ones that should be taken into account in the design of connectors for aluminum conductors.

TABLE III

DIFFERENCES BETWEEN ALUMINUM AND COPPER IMPORTANT TO CONNECTOR APPLICATIONS

	Aluminum (EC H19)	Copper (H.D.)
Modulus of Elasticity	10,000,000	16,000,000
Tensile Strength, psi	27,000	64,900
Yield Strength, psi	24,000	40,000
Brinell Hardness	50	103
Thermal Coef. of Expansion, 1°C (linear)	23×10^{-6}	16.4×10^{-6}
Surface Film	Insulating	Semi-Conducting
Electromotive Series, Volts (from hydrogen)	1.70 (+)	0.344 (-)

D. Thermo-Elastic Ratcheting Failures

It was noted that the yield strength of a typical hard drawn aluminum conductor is almost one-half that of a hard drawn copper conductor of the same size. Therefore, when tightening a copper body clamp over an aluminum conductor, pressures may be easily developed which are beyond the yield strength of aluminum and this will cause the metal to flow out in permanent deformation. The maximum mating pressure that can be sustained will be the relatively lower yield strength of the aluminum. Further tightening is inevitably followed by further permanent deformation. This is so important that I would like to put the matter in another way. In tightening any bronze body connector, we generally find that sufficient torque on the bolt has been used so that the yield strength of the aluminum conductor was exceeded. What happens then, is that projections of the conductor strand tops or projections in the clamp body will come under very high unit stresses and they will deform quickly to give a bearing area which can support the stress. That bearing area in a matter of a few minutes turns out to be an area which will produce the yield strength stress of the aluminum. If the connector is tightened again, the same procedure is repeated. The supporting area increases again to sustain the new stress and consequently, more aluminum is extruded into former voids or out of the connector body.

Since the thermal coefficient of expansion of the aluminum conductor is 40% greater than that of the bronze connector body, when the joint is heated under load, the aluminum conductor will expand at a much faster rate than the connector body. The result is that mechanical pressures on the aluminum conductor will increase rapidly until its yield strength is exceeded at which point the aluminum will again flow out in a permanent deformation. When the load has been released, the joint cools but as a result of the stress flow-out and greater contraction rate, the aluminum conductor is somewhat smaller in metal bulk than it was previously and the clamping pressure drops to a value much lower than it was originally.

This so called thermo-elastic ratcheting effect may continue until the electrical contact is so poor that the new I^2R losses introduced very appreciably contribute to heating the entire connector. The point where a runaway thermal condition can start is when the contact resistance added to load heating generates more thermal energy than can be dissipated. This usually ends up by burning-up of the connector or its loosening to a point where the circuit is interrupted. We have seen a great many of this type of failure as well as that due primarily to corrosion. Yet many cases of thermo-elastic ratcheting failure have been erroneously ascribed to corrosion between copper and aluminum components.

E. Corrosion Failures

Corrosion failures in connectors can and do occur. We have already noted the large difference of potential between aluminum and copper in solution, amounting to about two volts. Hence, the presence of an ionizable salt for example, in solution leads to a bi-metal cell in which

current flows from the aluminum anode thru the electrolyte to the copper cathode and then returns via a metallic circuit. There is usually a metallic return circuit somewhere but if not, galvanic action can still take place thru small local concentration cells wherein the concentration of salt in one area may differ from that of another and, as a result, a circulating current flows with one area being slightly higher in potential than the other. In either form of electrolysis, the result is to destroy the aluminum conductor at the regions of activity. The process is complicated by the build-up of decomposition products and the evolution of gases at the electrodes. It is a fairly complex task to analyze the exact mechanism in any given circumstance.

Several means are in general use at present to overcome or mitigate such electrolytic corrosion problems. In point of time the first was to plate a copper body connector with either tin, zinc or cadmium since these metals are closer in the electromotive series to aluminum; they will develop much less potential difference and hence much less electrolytic current. A second very popular method is to seal, cover or protect the bi-metal junctions so that moisture and ionizable contaminants cannot enter. These are reasonably effective under most normal atmospheric conditions (where thermo-elastic ratcheting is not present) and indeed there are many locations where no particular means need be taken to avoid bi-metal galvanic corrosion simply because there is sufficient cleansing rain fall, and insufficient electrolyte present to cause the troubles discussed. However in the connector designs currently in use both of these methods have been found unreliable in severely corrosive environments.

A third method, of definite merit, is to make use of the "mass anode" principle wherein the lessnoble metal of a bi-metal circuit is much larger and surrounds the more noble metal. Practically, this means the connector body must be of large dimensions and of aluminum. The anode current density of the corrosion cell will then be reduced, thus reducing the amount of anode metal taken into solution. Concurrently, the larger aluminum connector body will provide better pressure distribution on the conductors and since it will operate considerably cooler than the conductors, the effects of thermo-elastic ratcheting described previously, may be eliminated or made negligible. Combining a well designed, large aluminum connector with a good sealing paste should satisfactorily limit galvanic corrosion problems for aluminum-to-copper connections at all but the most severe industrial and sea coast areas. In such areas, however, the connector life can be expected to be shortened by the steady galvanic attack due to the ever present strong electrolytes.

F. Ideal Solution to Copper-to-Aluminum Connection Problem

It would appear possible to set up a series of requirements that an aluminum-to-copper connector must meet in order to perform satisfactorily and reliably in <u>any</u> natural, corrosive atmosphere. I would like to set these down for your examination.

(1) <u>The aluminum and copper conductors must be kept as far apart as possible to avoid the possibility of an electrolytic bridge.</u>

This is a very real requirement. On the West coast there are places where I have seen conductors separated in a split bolt connector by a quarter inch that were completely bridged over, the connector forming the metallic path, the bridge forming the electrolytic path and the aluminum has disappeared in a matter of three months. Those are very rough, very severe conditions, but they do exist.

(2) <u>The exposed boundary of any bi-metallic junction must be kept as small as possible.</u>

This is obvious; however it was apparently not appreciated in some of the early connector designs which had enormous bi-metallic plates or washers. Some even had holes punched in the surface to make them lighter, thus exposing additional bi-metallic edges for attack.

(3) <u>The exposed boundary of the bi-metallic junction must not be involved in the main current passage.</u>

It is desirable that if the bi-metallic junction does get into trouble, we don't want the connector's primary function immediately jeopardized as a result. Some foreign connector designs take advantage of this principle, as we shall see later, by placing the bi-metal junction at some distance from the current contact area.

(4) <u>The exposed boundary of the bi-metallic junction must be permanently sealed from contact by moisture or other air-borne contaminents. The connector must also provide an inner barrier to prevent strand wicking between the two parts of the connector.</u>

This simply means that both the exposed bi-metallic boundary and any inner paths to the bi-metallic surfaces (for example, via the strand interstices of a stranded conductor) must be sealed and blocked. Very few American connectors completely fill this requirement.

(5) <u>The difference in tensile and elastic properties of aluminum and copper must in no way affect the performance of the connector.</u>

(6) <u>Differences in thermal coefficients of expansion between aluminum and copper must in no way affect the performance of the connector.</u>

Requirements (6) and (7) are needed to maintain tight connections and to prevent thermo-elastic ratcheting.

(7) The connector must provide a stable, efficient, simple means for attachment to the aluminum and copper conductor which it joins. The completed connection should withstand a tensile load compatible with its service requirements and with such additional margins of strength as to permit it to meet foreseeable emergency requirements.

After talks with a considerable number of utility people, the opinion was expressed that they would like to have at least 50% of the conductor strength in any non-tensioned line connector put on a line. I am inclined to agree with them.

(8) The connector design should be relatively inexpensive to manufacture and should readily provide a size range consistent with the sizes of conductors normally used.

This is, of course, sound engineering and consistent with American practice in all fields.

G. Kaiser Research Program on Aluminum Conductor Fittings:

Late in 1952, the Kaiser research laboratories embarked on an ambitious program to evaluate every type of connector fitting available commercially for use with aluminum conductors. First efforts are being concentrated on overhead distribution accessories but later building and underground cable fittings will be included.

Some thirty-three connector manufacturers supplied units for the tests and over 9000 connectors representing many types and kinds are being studied.

The test program consists of a relatively elaborate laboratory cyclic aging operational test, supplemented by field tests in various highly corrosive environments of the United States. Essentially all distribution type connectors and fittings are tested under superimposed conditions simulating those to be encountered in moderate to severe environments. The fittings are attached to their proper size aluminum, ACSR or copper conductors in the manner as prescribed by the manufacturer both with and without the recommended connector aids. The conductors are all mechanically loaded at tensions comparable to those permitted in service and some of these will also be vibrated continuously. All of the connectors are cyclically current loaded at a maximum value corresponding to 125% of the full rated current of the conductors involved.

Three environments are used during the test. The first is represented by a 1% sea salt fog, the second, by a distilled water fog and the third by an, as yet, unselected reagent fog, representative of a heavy

industrial atmosphere. In each case the environment cycle is shown by the following program:

First half cycle (3 hrs. duration):

	Sequence	Minutes
Load current on:	1	180
Sea salt (or distilled water, or industrial reagent) fog:	1	105
Dry (sun lamp plus warm air):	2	30
Fresh water fog:	3	15
Dry (Sun lamp plus warm air):	4	30

Second half cycle (3 hrs. duration):

As above but load current off.

Electrical resistance and temperature rise taken throughout the test runs are used to establish criterion of stability. At the conclusion of each test, the units are subjected to a short time overload and short circuit current. Representative samples are tested for physical properties and chemical, radiographic and metallographic analysis are carried out to determine the extent of changes involved.

Figure 1 shows one of our field test stations where supplementary data on the connectors are being obtained. This is located at Yaquina Head on the Pacific Ocean near Newport, Oregon and represents an unusually severe marine environment. Technical papers describing the results of our connector tests will be issued from time to time, the first being scheduled for the Winter of 1955.

H. Currently Available Fittings for Aluminum Conductors:

I would like now to show you a group of photos illustrating some of the many varieties of American and European connectors which are under investigation in the laboratory. It is of interest to examine the different types of commercially offered connectors for aluminum conductors from the standpoint first, of their service requirements and second, how they meet the ideal requirements tabulated above for aluminum-to-copper connections in severe corrosion environments.

Figure 2 shows a number of types of split bolt connectors. Some are direct adaptations of connectors used on copper conductors with the addition only of tin plating. Others have large bell-mouthed washers to assist distributing the load on the aluminum conductor. Others have bi-metallic washers whereas still others have heavy aluminum separator bars with copper inserts. Some have aluminum alloy nut and bolt, others are plated or unplated

bronze. Figure 3 is a close-up of a bronze body split bolt connector with two bimetallic washers for enclosing the aluminum conductor.

Figure 4 shows a group of parallel groove clamps. Again some of these are tinned bronze whereas some are aluminum with and without cadmium plating. Most have plated steel nuts and bolts but one type is all-aluminum including an aluminum bolt and nut (treated to prevent freezing). Most have soldered-in copper inserts for aluminum-to-copper connections but one type relies only on its extra thick cadmium plating. They all have the desirable, wide conductor separation not found in split bolt clamps. One type, not shown in the figure, has the copper insert keyed and cast into the aluminum body to avoid retained solder flux problems. A few of the bolts have spring type lock washers.

Figure 5 shows a representative group of two-bolt and "U" bolt clamps. They represent a variety of concepts of aluminum-to-aluminum and aluminum-to-copper connector body metals. One of the "U" bolt clamps is entirely of aluminum alloy with soldered in copper liners in the lower section.

Figure 6 represents two kinds of vise type clamps, one of bronze body with zinc plating, the other all-aluminum alloy with unbonded copper-aluminum bimetal strips forming the contact area in one set of jaws.

Figure 7 shows several types of compression connectors. The upper set represents the steel and aluminum sleeves for a tension splice on an ACSR conductor. Of the central two sleeves, the left is an aluminum sleeve for full tension splicing two all-aluminum conductors. The right sleeve is of aluminum but has a soldered-in copper sleeve on one side. It is a non-tension splice for aluminum-to-copper connections. The lower right unit is a figure "8" form made of tinned copper also for aluminum-to-copper connections. The central lower unit is a heavily tinned copper tap connector which is compressed around the conductors with terrific force. The lower right unit is also for copper-to-aluminum connections and is similar to the coaxial sleeve type described above.

Figure 8 shows two types of automatic line splices suitable for lines under tension. The upper contains a double set of jaws on each side for separately gripping the steel and the aluminum strands of an ACSR cable. The lower unit is for an all-aluminum conductor.

Figure 9 shows a variety of stirrup tap clamps for use on lines where taps may be changed frequently. Every variety of aluminum and copper combination is represented in this figure. One shows a protective synthetic film at the bimetallic junction; others show no protection. In all cases the aluminum-to-copper junctions are made by mechanical compression.

Figure 10 shows several types of hot line clamps used with aluminum and copper connections. Some have tinned bronze bodies, others are of aluminum and one has a cadmium plated aluminum body. Invariably the copper tap sections are of plated bronze. Some of the units have heavy spring members for maintaining pressure at the contact. One type is in two parts (upper right side of the figure) with the line member compression crimped to the main line by hot stick. The tap section is also compression connected to the tap conductor and the two units are joined by a clamping bolt using a hot stick.

Figure 11 shows a group of popular, light weight dead-end grips. None of those shown require bolts. Two types have slide gripping wedges; one type has a split conical sleeve for automatic gripping and another has a standard compression sleeve fitting. The upper dead-end is a preformed aluminum alloy wire type using a 10% reduced diameter bore and a surface grit. The other dead-ends have either galvanized steel or bronze wire bails with aluminum alloy gripping sections.

Figure 12 shows a group of heavier dead-ends combining snubbing and bolting action. Bodies are of aluminum alloy or, in one case, of galvanized malleable iron. The bolts are invariably of galvanized steel.

All of the above figures have shown various types of fittings as produced by American manufacturers. Figure 13 exhibits a number of British, German, French and Italian connectors for use with aluminum conductors in the applications we have been discussing. The two tap connectors in the second row are radically different from each other in principle although both are designed for aluminum-to-copper connections. The left unit is a so-called "sacrificial" type combining an aluminum parallel groove clamp and a paste filled closed end aluminum tube which is slipped over and snugly fits the copper conductor. By this means the only bi-metal boundary subject to galvanic corrosion is placed at some distance from the electrical contact surface. Only the aluminum tube therefore slowly sacrifices itself. The unit on the right side is a British tap design in which the copper member is screwed into the 4-bolt aluminum clamp. Where the aluminum and copper meet, the aluminum body is milled out to form a substantial cavity around the copper. The cavity is then filled with a soft sealing material and covered with a heavy polyethylene film. By this means the exposed bimetal boundary is protected from direct contact with any surface electrolytes.

This same principle is seen on the "U" bolt clamp and parallel groove clamp of German origin in the next lower row and also in the bimetal terminal at the upper left and in the automatic line splice at the bottom. Note the two combination loop dead-end and tap units in the third row.

Figure 14 shows a variety of hand tools, some entirely mechanical, others hydraulic powered, for attaching compression connectors on the smaller sizes of conductors. The upper right hand tool is a hand-operated hot line type.

Figure 15 shows a representative group of products used for assisting and protecting the connection. It is suggested that such products be given the generic name of "Connector Aids". Further they can be broken down into descriptive titles as follows:

(1) SEALING PASTE: A jell-like paste to keep air and moisture, etc., out of the contact area. Examples: Neutral greases, heavy bodied jells, extensible films, etc.

(2) CONTACT AID: Metallic grit in a light vehicle; field sprayed metallic surfaces; active etching preparations, etc.

(3) SEALING-CONTACT PASTE: Providing a combination of the functions of (1) and (2) above. Example: A metallic, cutting particle incorporated into a heavy bodied neutral grease or other extensible medium.

(4) COVERALL: An enclosure over the entire finished connection. Examples: Molded on plastic covers; self-sealing, hand applied mastic compounds; tape; sprayed on films, etc.

On the basis of the above nomenclature, Figure 20 shows from left to right: A paint coverall, a sealing paste, a plastic coverall, a sealing-contact paste and another sealing paste.

I. Development of the ALCUnector:

Our work on connectors and examination of numerous service aged fittings from all over the country has naturally led to study of original designs overcoming the deficiencies found. Based on this experience and the ideal design criteriae previously set down, an aluminum-to-copper connector unit has been developed at Kaiser and is now under critical evaluation in the laboratory, at field test stations, and in actual service in every natural corrosive environment in the country.

This connector consists essentially of an aluminum member butt joined to a copper member in such a way as to form a strong, high conductance bond which remains permanent with regards to mechanical and electrical properties. The small bimetal boundary is permanently protected by a suitably shaped, tough seal of high grade elastomeric compound, pressure molded to the connector and bonded perfectly to both metals. Unique electronic and dielectric methods are used to insure the joint quality and the seal to metal bond.

Figure 16 shows the ALCUnector unit for a straight-through splice using compression sleeves for attaching the aluminum and copper conductors. The upper left unit in Figure 19 shows a typical pull test on such a joint with solid members. Note the necking in the aluminum section at 4000 lbs. The two units at the right show the completed connector with heavy seals in place. Finally the lower unit shows an ALCUnector joining a No. 4, 7 strand aluminum conductor to a No. 6 solid copper conductor. Such a joint has about 75 micro-ohms resistance from conductor to conductor and will withstand a 500 lbs. tensile load indefinitely. Breakage occurs by the pulling out of the conductor at the compression sleeves. By using larger sleeves with more crimps, the full breaking strength of the conductors can be achieved.

The ALCUnector thus appears to provide a safe, trouble-free transition medium for aluminum-to-copper connectors under all operating conditions in any natural environment. The form of the connections on either side of the hermetically sealed bond of aluminum-to-copper may be varied commercially to meet many types of connection requirements. For example, either the copper or aluminum, or both compression barrels may be replaced by solid ductile conductors. Or, one side may have a right angle offset and a split sleeve for easy compression connection to a main line. Or, one or both sides may have lug

terminations with drilled tongues. Figure 17 shows three forms of ALCUnectors suitable for various purposes.

The ALCUnector transition unit provides the following advantages:

1. It is simple, light and designed to be readily installed in the field with tools and techniques already proven and available.

2. It provides the farthest and most effective separation of the two conductor metals with regards to external exposed surfaces.

3. It provides a positive, metallic barrier between the internal surfaces of the two conductors joined.

4. It provides a permanent, long-path seal over the smallest possible boundary of the two metals joined.

5. It provides a very high strength, low resistance (80% IACS) metal to metal bond for current passage. This path cannot become involved in a galvanic cell corrosion process.

6. It provides perfect match of mechanical properties of each conductor to each connector side; this eliminates the so-called "cold flow" problem.

7. It provides perfect match of thermal expansion properties of each conductor to each connector side. This virtually eliminates the differential "ratcheting" problem experienced under load changes in other connector types.

8. It provides a variety of conductor attachment methods including the positive, high pressure, crimping method, which for like metals, has proven completely satisfactory in many thousands of installations over many years of service.

9. The design is adaptable to many applications and a wide range of conductor sizes. It lends itself to economical, large-scale commercial production.

The ALCUnectors now undergoing tests are operating on Utility systems in the areas as shown on the map of Figure 18. Test results after one year will be summarized and it is hoped that a detailed technical paper will be published early in 1955.

I would like to call your attention to the fact that we have no intention of entering the connector manufacturing business. If the ALCUnector design proves to be the answer sought for in aluminum to copper connections we will make it available to any reputable accessory manufacturer who may wish to produce it on a commercial scale. Our real concern is that accessories be made available to you, which are reasonable in cost and satisfactorily complement the inherent good performance of aluminum conductors.

J. Glass Fiber Brushes for Cleaning Electrical Contacts:

In closing this rather long, and I fear somewhat rambling presentation, I would like to tell you something about the excellent performance of glass fiber brushes when used to clean the surface of an aluminum conductor prior to connection. We have found that in comparison to the usual steel wire brushing, or draw filing or sanding, glass brushing has the following advantages.

1. Surface oxide films are removed from conductors with very little pressure compared to other mechanical means. The glass fibers more nearly match the hardness of the oxide layer than do steel brush bristles.

2. Gouging of the base metal is kept to a minimum because the glass fibers are exceedingly fine. The result is a fine satiny finish that has many more points of contact than normally obtained on a steel-brushed or filed surface.

3. Shape of the glass brush conforms easily to the strand forms. Stranded cable is readily brushed lengthwise, making clean contacts between the strands. This is more difficult with a steel brush.

4. No heavy metal particles are introduced in the conductor which might tend to start galvanic corrosion.

5. Plated surfaces may be readily cleaned with a glass brush without danger of cutting through the plating.

6. Brushes are readily available commercially in a variety of convenient sizes, and may be obtained in a pencil-like holder which feeds the brush through as the fibers wear. Tapewound round brushes are also available, as well as larger, wide brushes suitable for cleaning large areas such as switches and bus bar terminals.

Figure 19 shows a 5/8 inch glass fiber brush being used to prepare the end of an aluminum conductor prior to insertion into a terminal. Comparisons of the profile appearance of glass and steel-brushed surfaces (at 100 x magnification) show deep scratches and high ridges in the steel-brushed surface, whereas the glass-brushed surface is more uniform and yields many more contact points in an electrical connection.

Glass fiber brushes are naturally used in a lengthwise direction along the lay of the cable because they need less pressure, and they work like a crayon. The surfaces between the strands are thus cleaned with little metal removal and without making transverse scratches which may lead to weakened strands.

The excellent conductivity of glass-brushed contacts has been confirmed by laboratory experiment involving the comparison of the surface resistance of aluminum bus bars cleaned by steel brushing with similar bars cleaned with a glass-fiber brush.

The aluminum bars, each 11/16" square by 5" long, were first smoothed on a shaper and then intentionally oxidized by heating, before being cleaned by brushing. Test bars were crossed at right angles, held together with a force of 1050 psi, and the resistance of the joint was measured with a Ductor ohmmeter. A current of approximately 100 amperes was used in the measurements.

Resistance of the wire-brushed contact surfaces was found to be 19 microhms, while the resistance of the glass-brushed surfaces was only 6 microhms. This is equivalent to 2.9 microhm-square inch transverse surface resistivity for the glass-brushed contacts as compared with 9 microhm-square inch for the steel-brushed contacts.

Although these tests were exploratory, and further research would be required to establish how the values are affected by pressure and other conditions, they give a clear indication of the advantages of using glass brushes in making connections.

May, 1954

EWG:f

Figure 1

Pacific Coast Conductor Test Station - Yaquina Head, Oregon

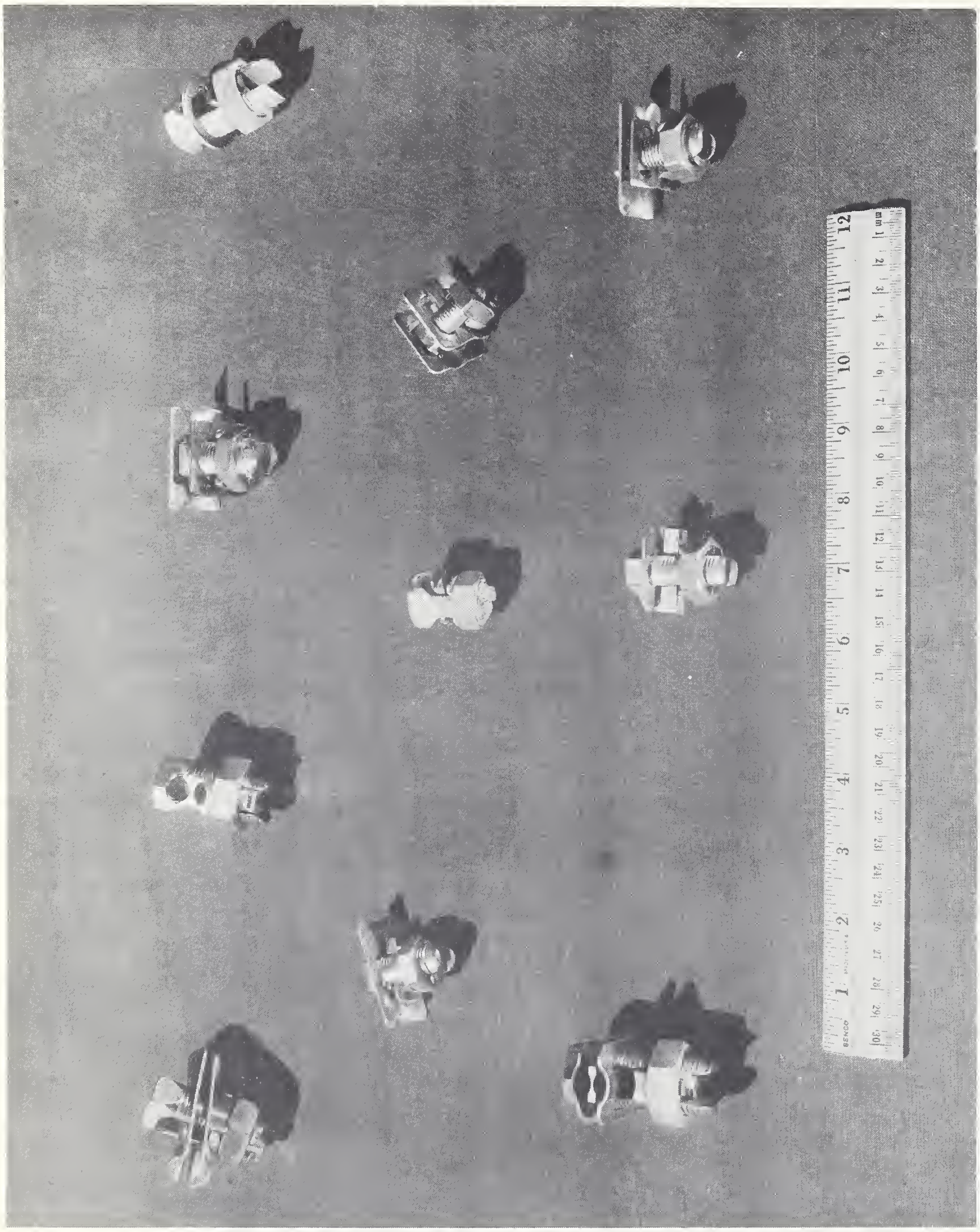

Figure 2

Various Split-Bolt Connectors Used With Aluminum Conductors

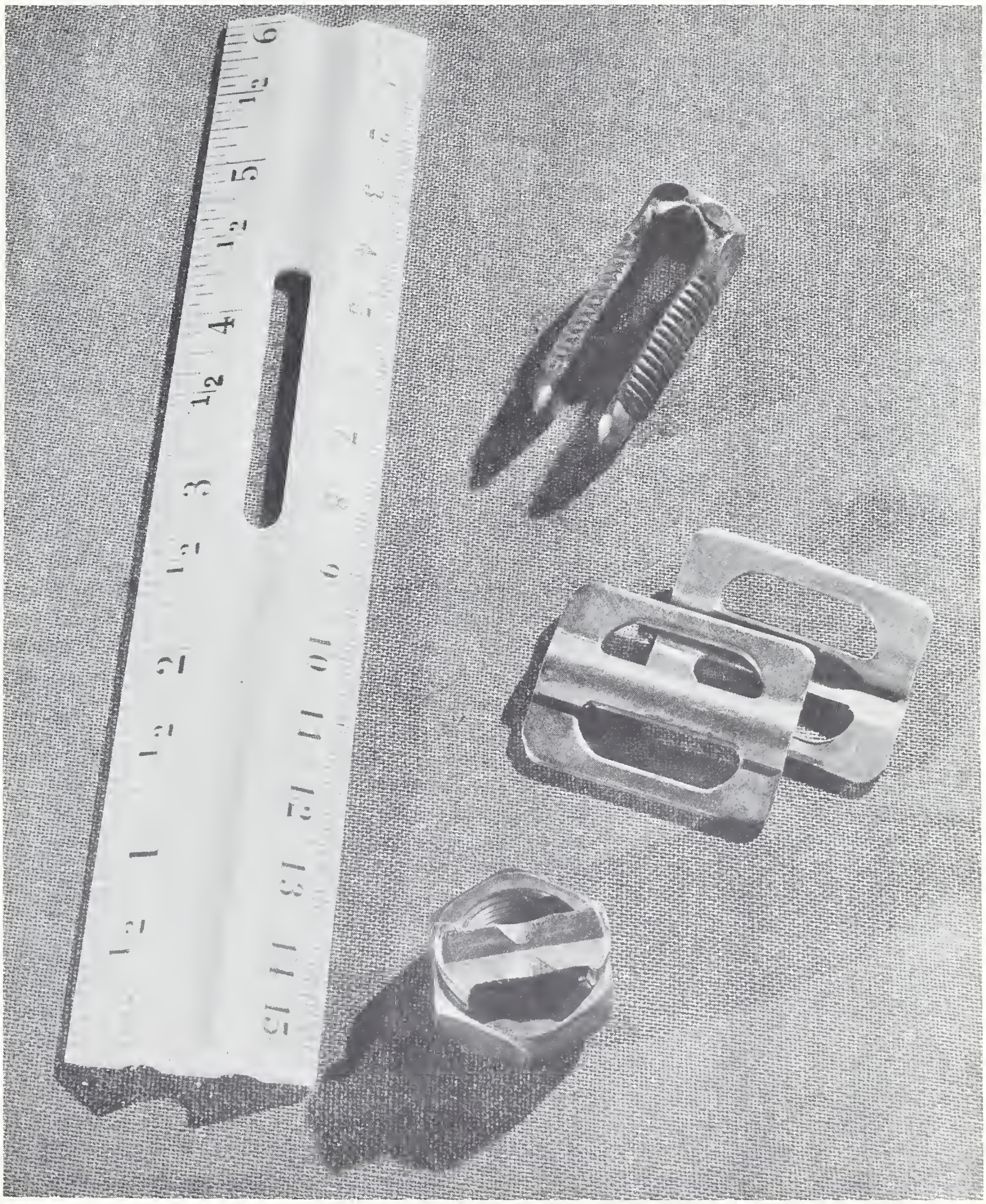

Figure 3

Close-Up of a Bronze Split-Bolt Connector With Bi-Metallic Washers

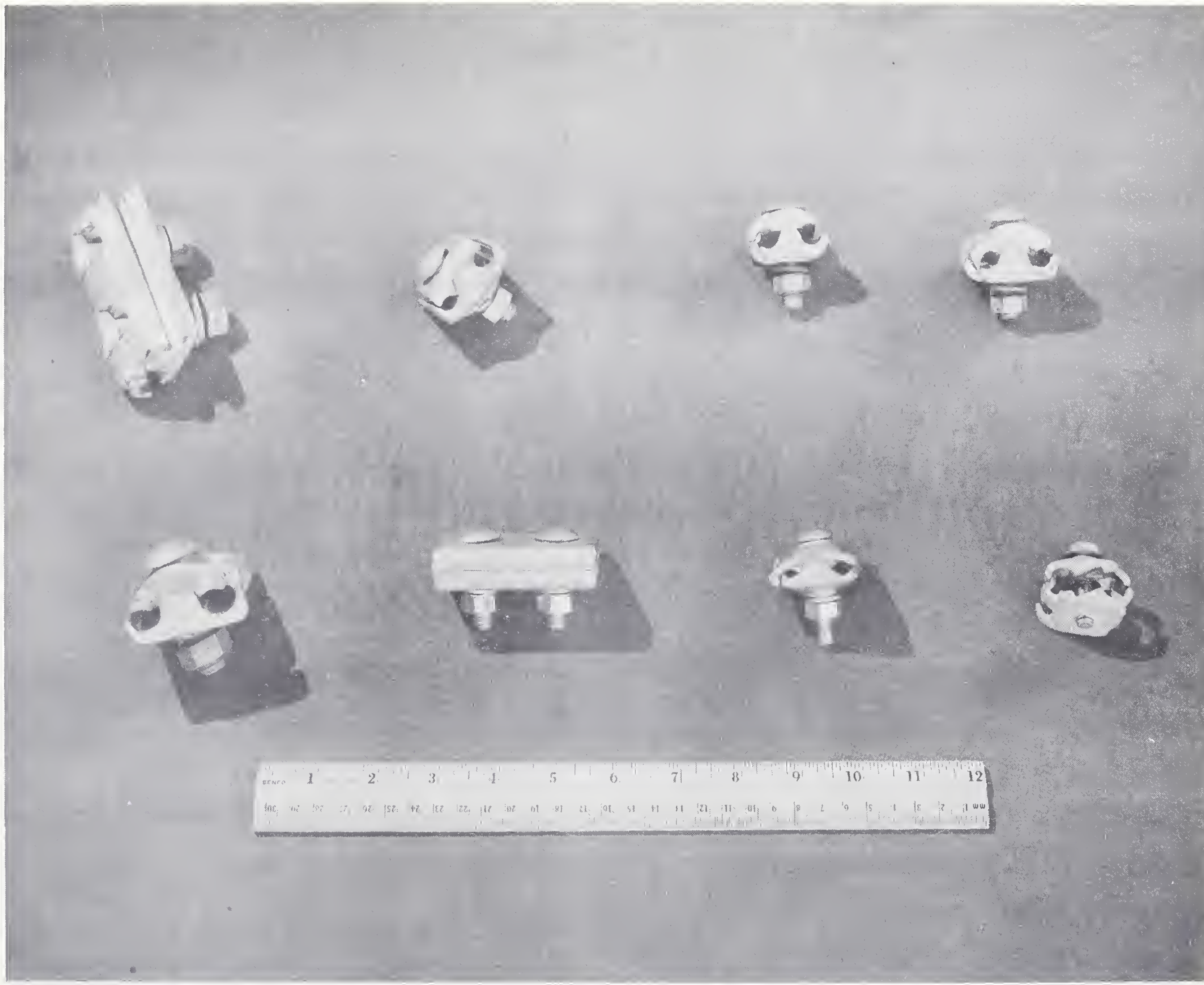

Figure 4

Various Single and Two-Bolt Parallel Groove Clamps

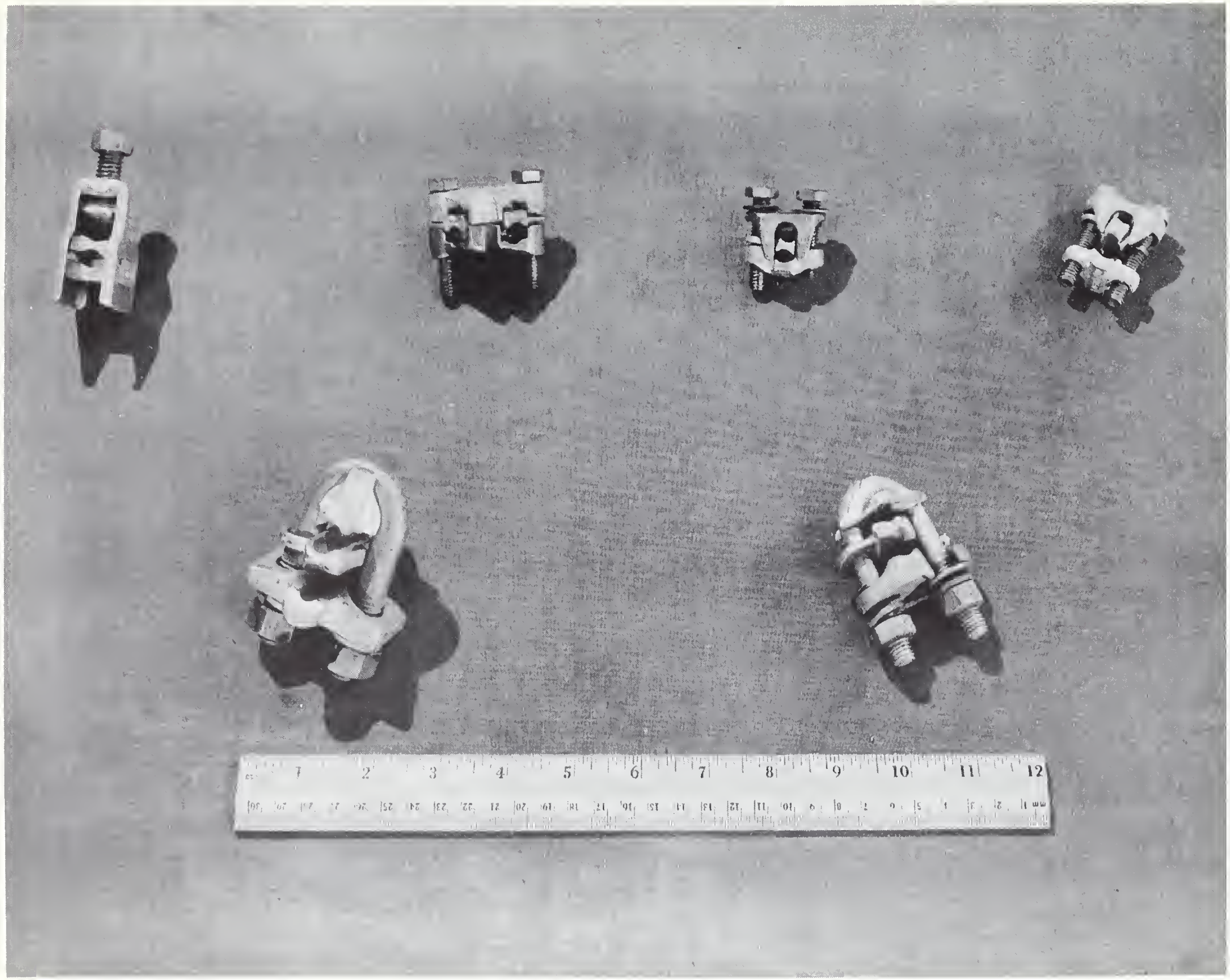

Figure 5

"U" Bolt and 2-Bolt Clamps Used For Aluminum and Aluminum-to-Copper Connections

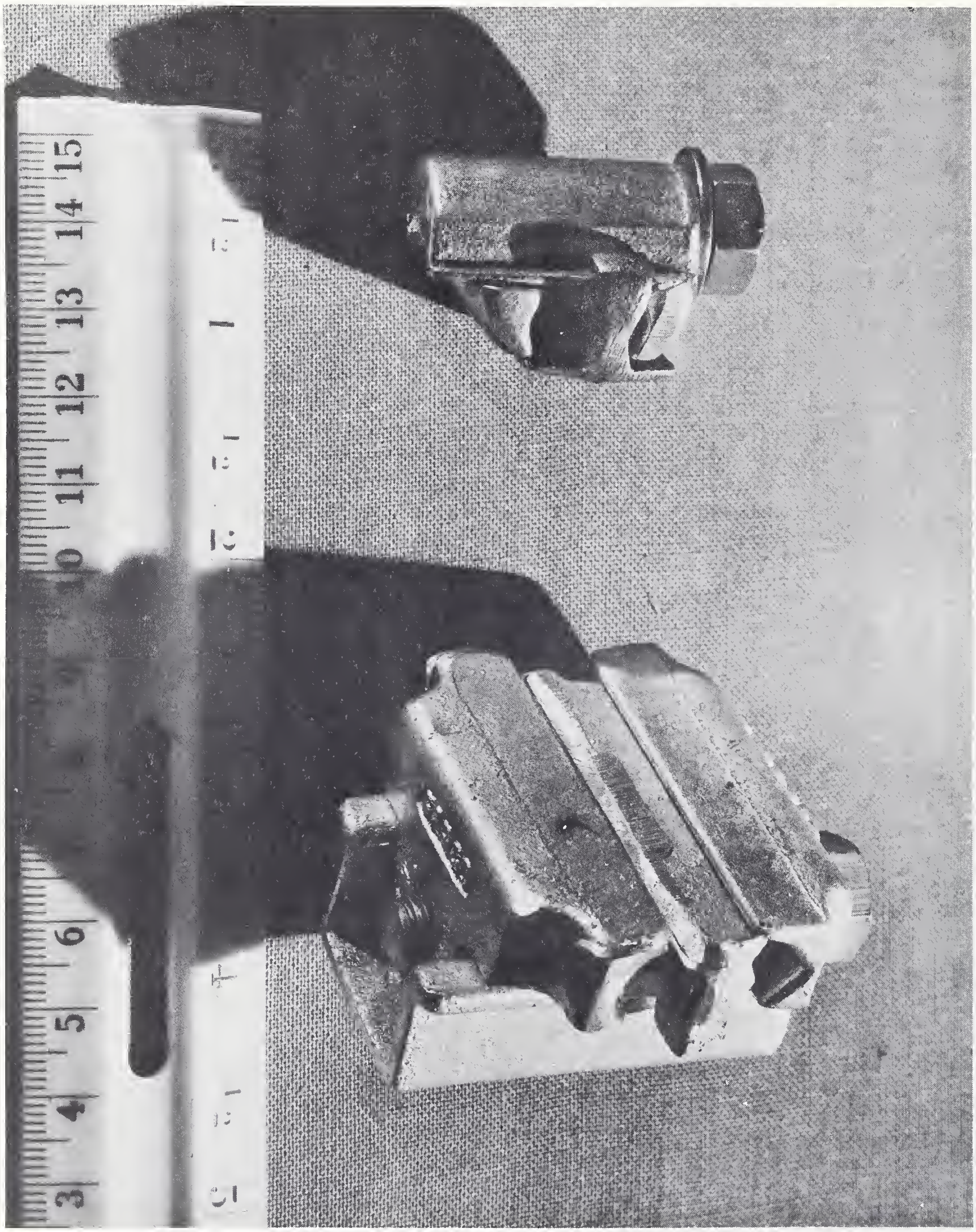

Figure 6

Vise Type Connectors, Plated Bronze and All-Aluminum

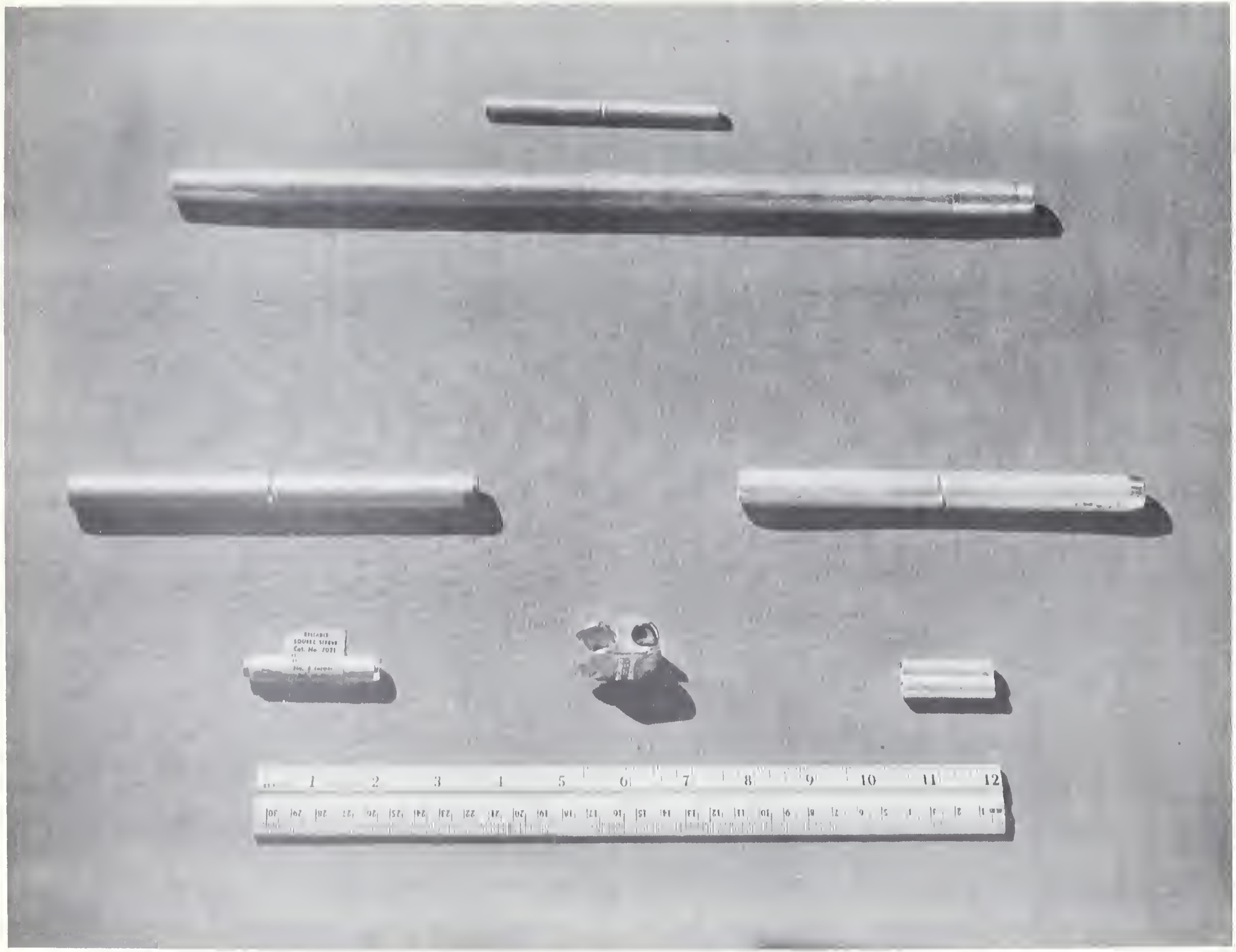

Figure 7

Compression Type Units for Tensioned and Non-Tensioned Connections, Aluminum-to-Aluminum, ACSR to ACSR, and Aluminum-to-Copper

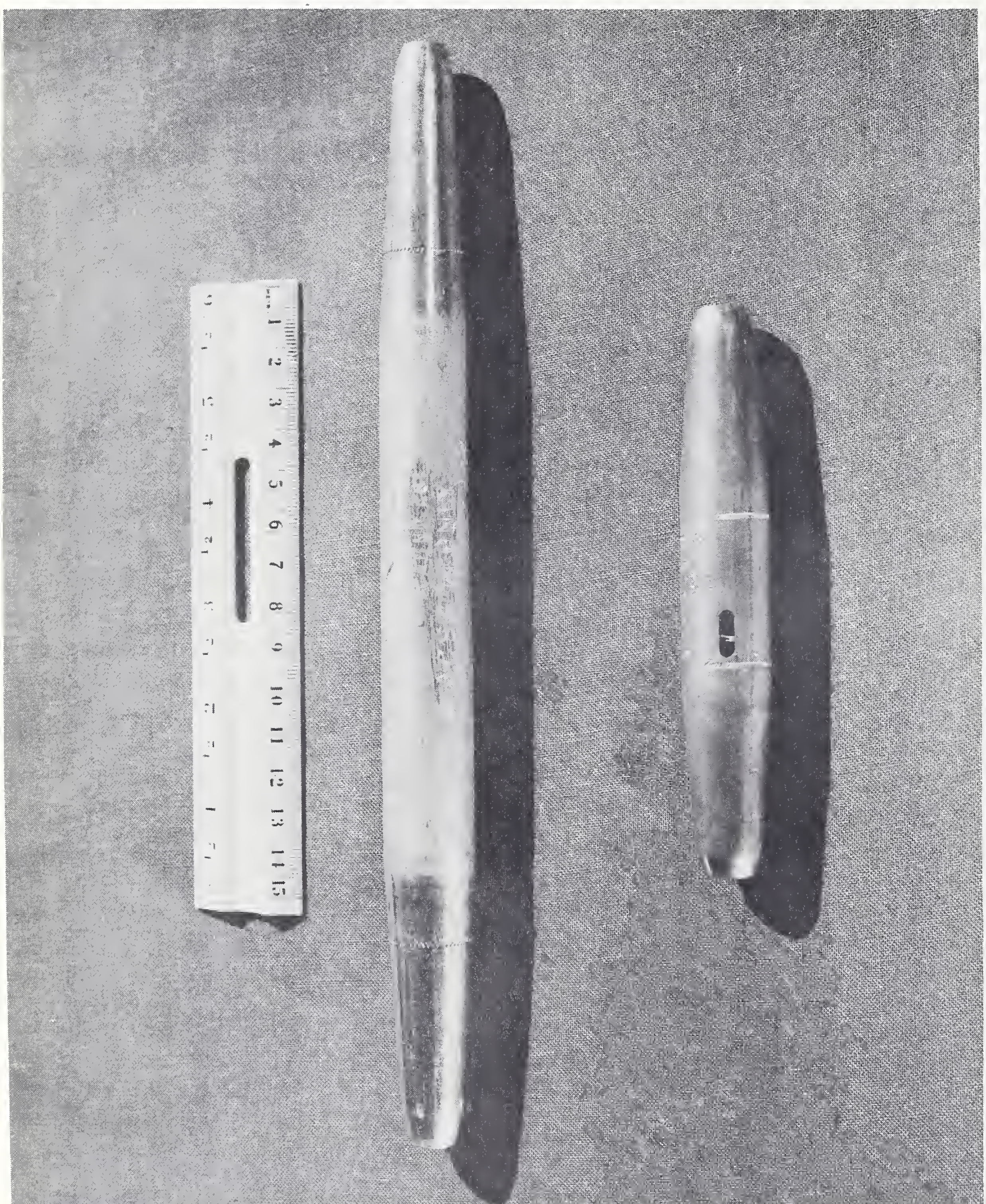

Figure 8

Automatic Line Splices. Upper - ACSR to ACSR;
Lower - Aluminum-to-Aluminum

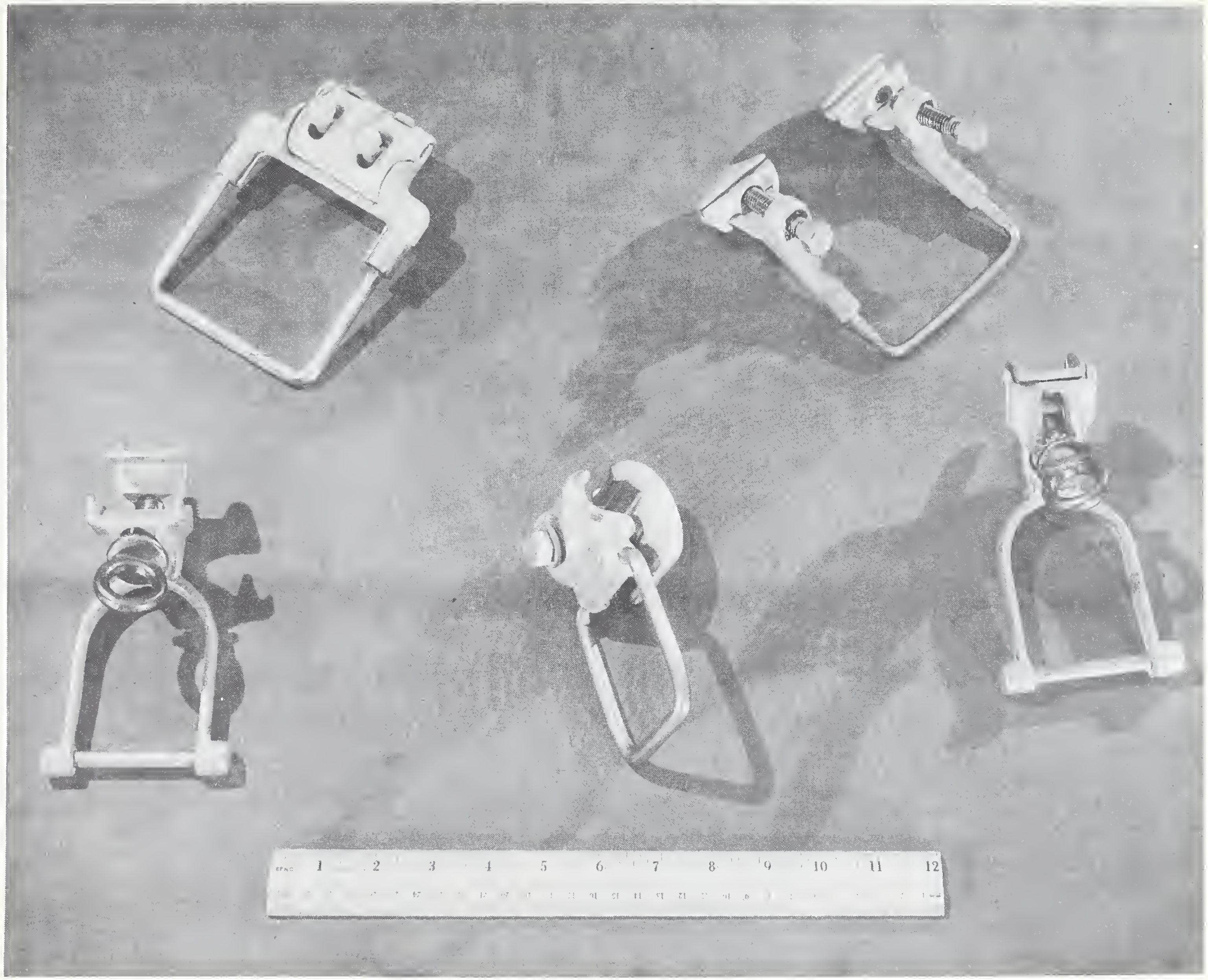

Figure 9

Stirrup Type Clamps with Various Combinations of Metals and Plating

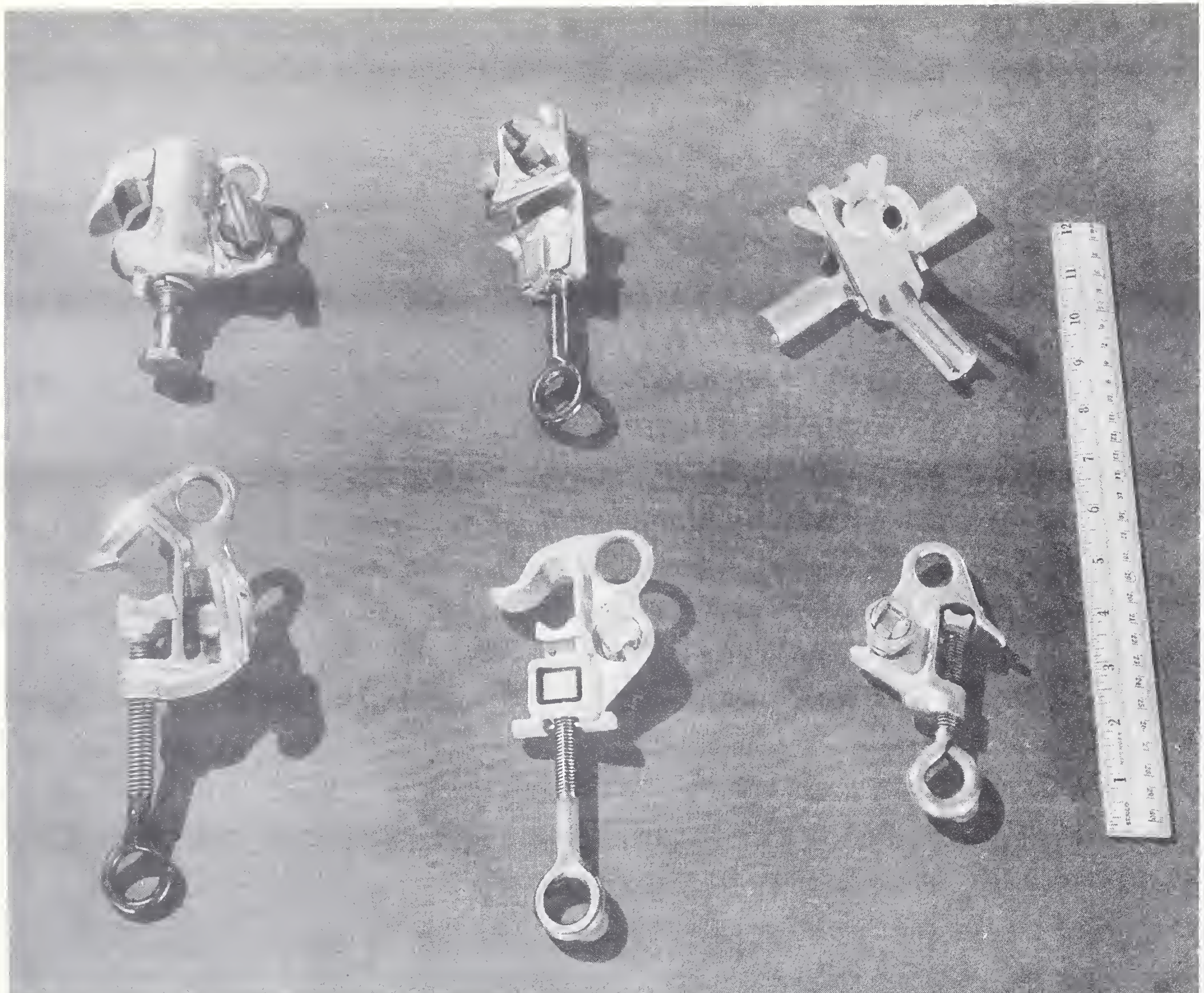

Figure 10

Various Types of Hot Line Clamps Used for Aluminum-to-Copper Tapping Circuits

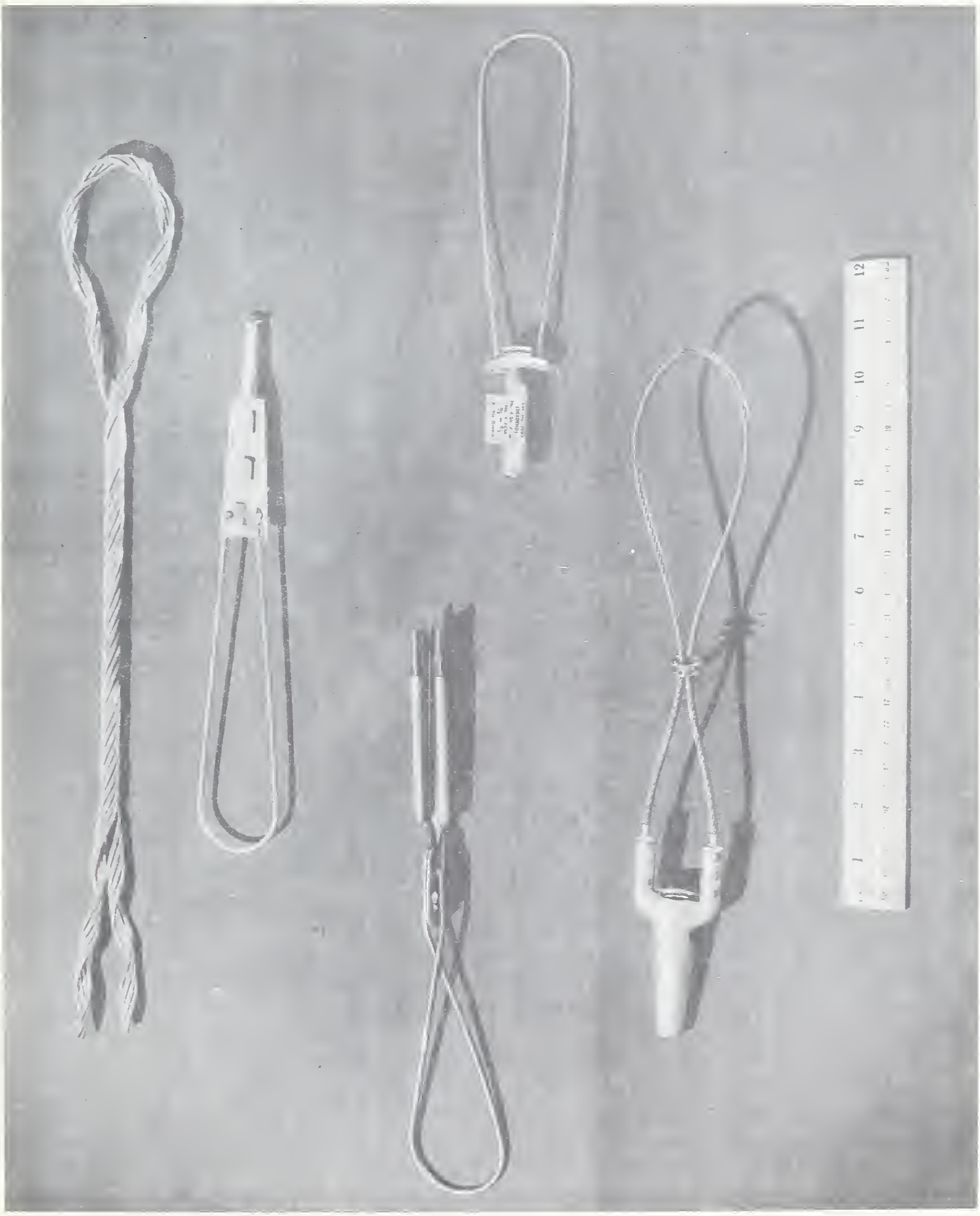

Figure 11

Light Weight Dead-Ends for Service Conductors

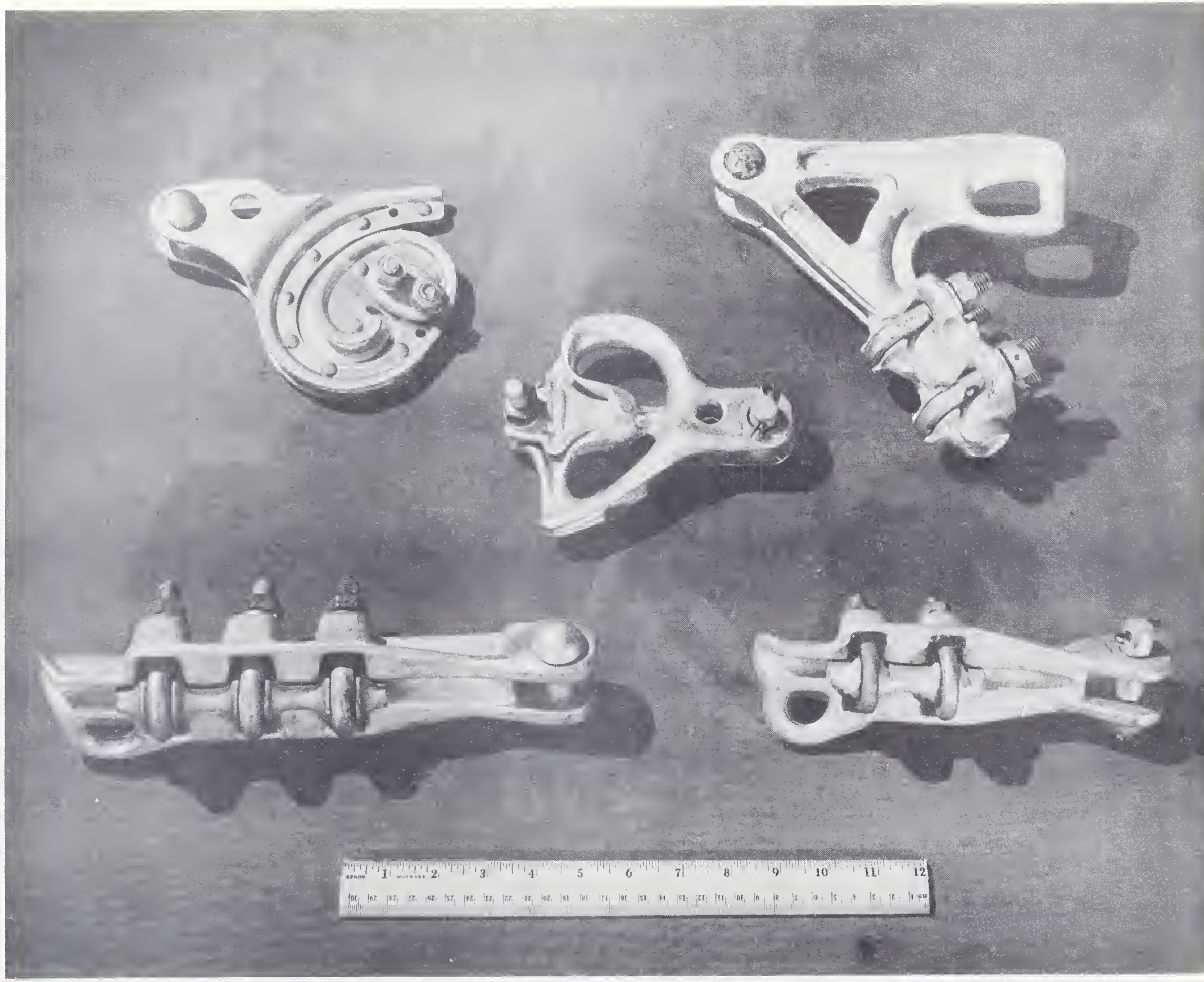

Figure 12

Heavier Duty Dead-Ends for Aluminum and **ACSR** Conductors

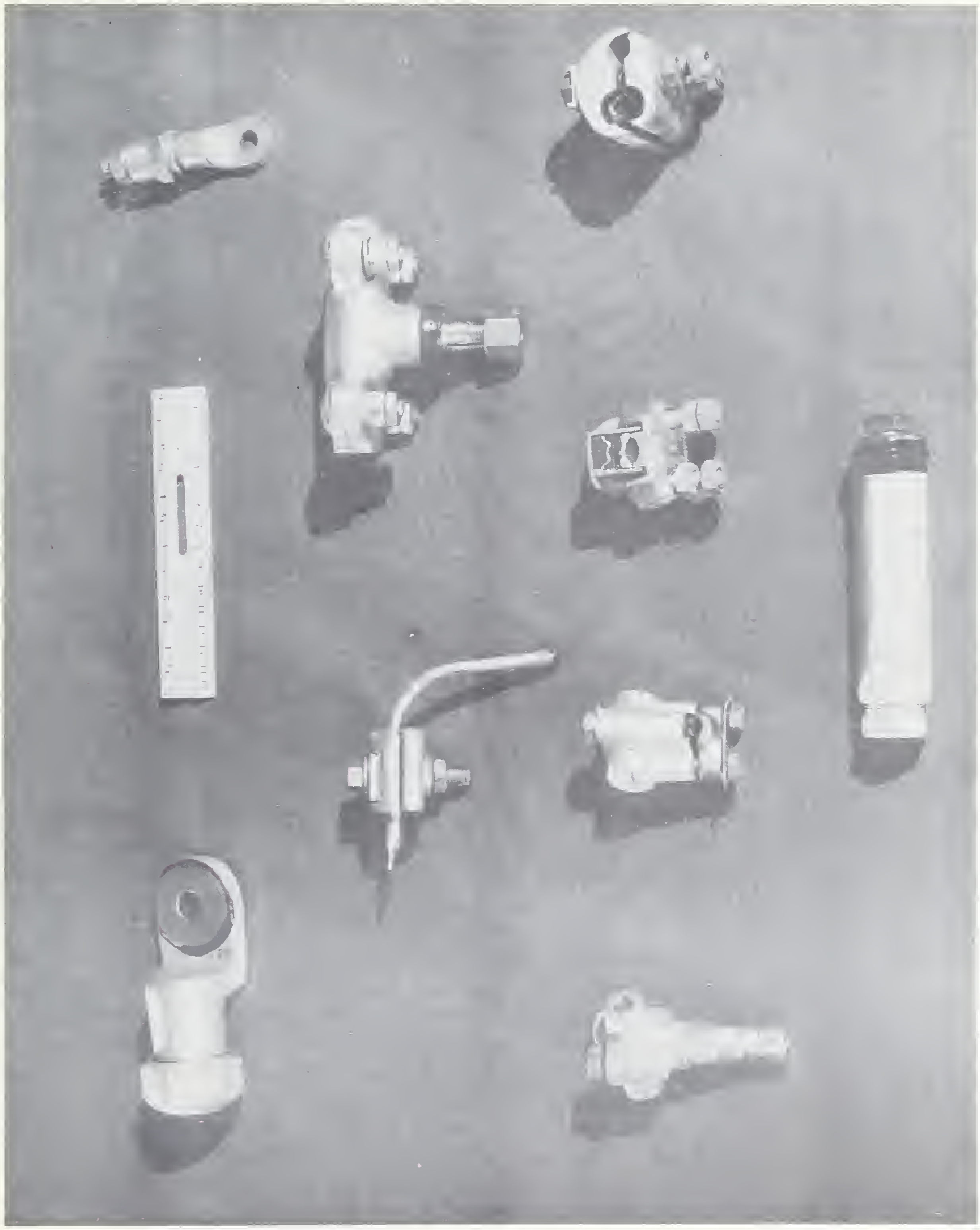

Figure 13

Typical Aluminum-to-Copper Connectors from England, France, Germany and Italy

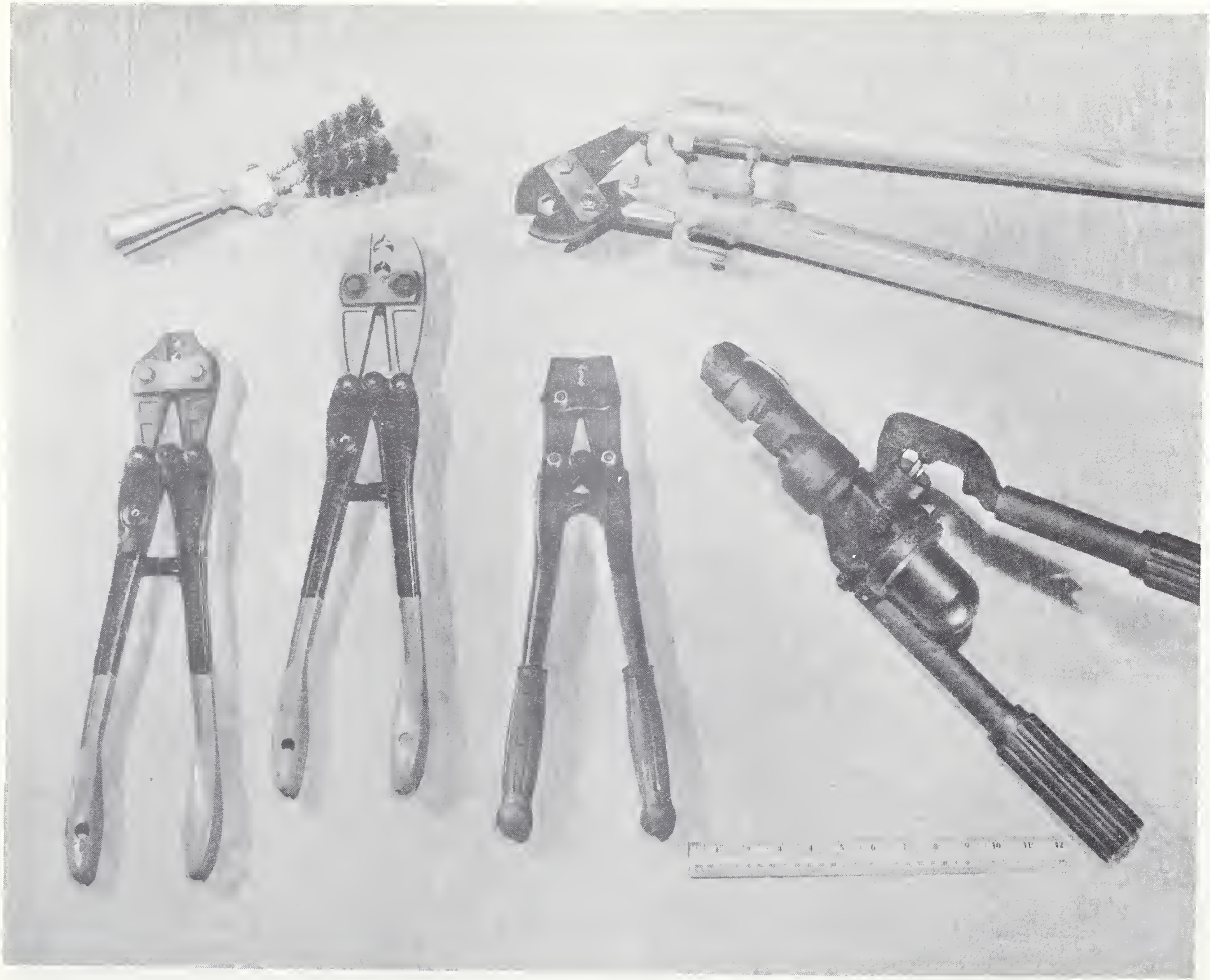

Figure 14

Mechanical and Hydraulic Hand Tools Used for Attaching Compression Connectors

Figure 15

A Few of the Presently Available Connector Aids

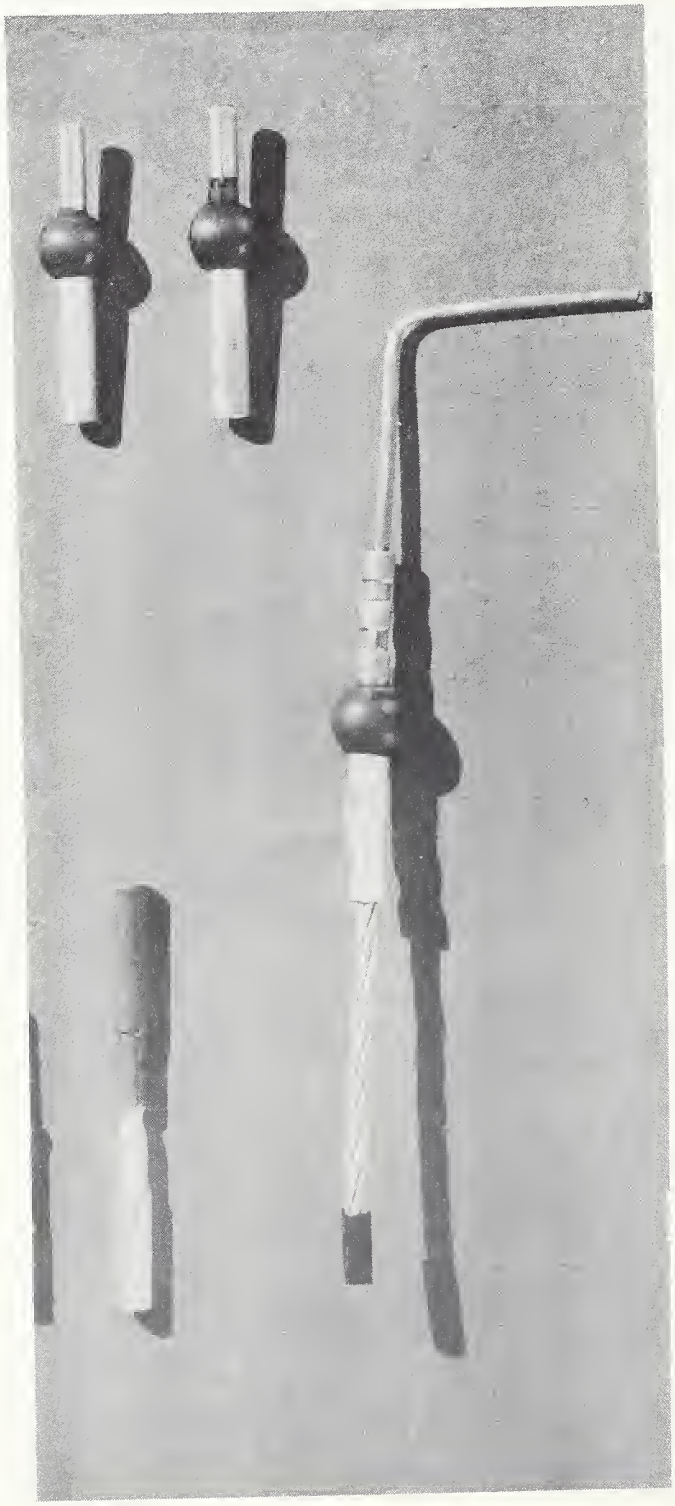

Figure 16

Evolution of an ALCUnector for Aluminum-to-Copper Connections

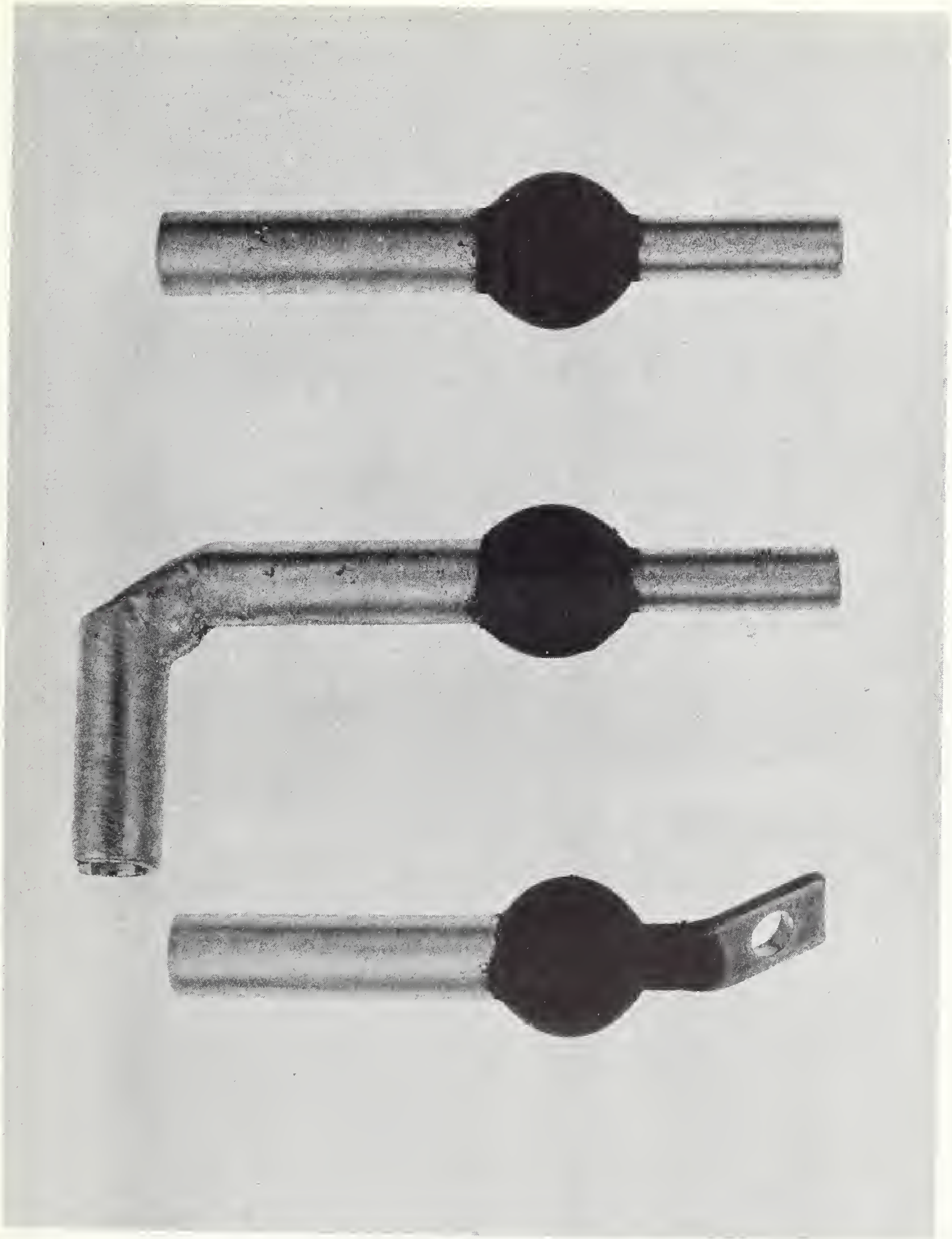

Figure 17

Three Ways to Use the ALCUnector

Figure 18

Areas in United States Where ALCUnectors Are Under Test

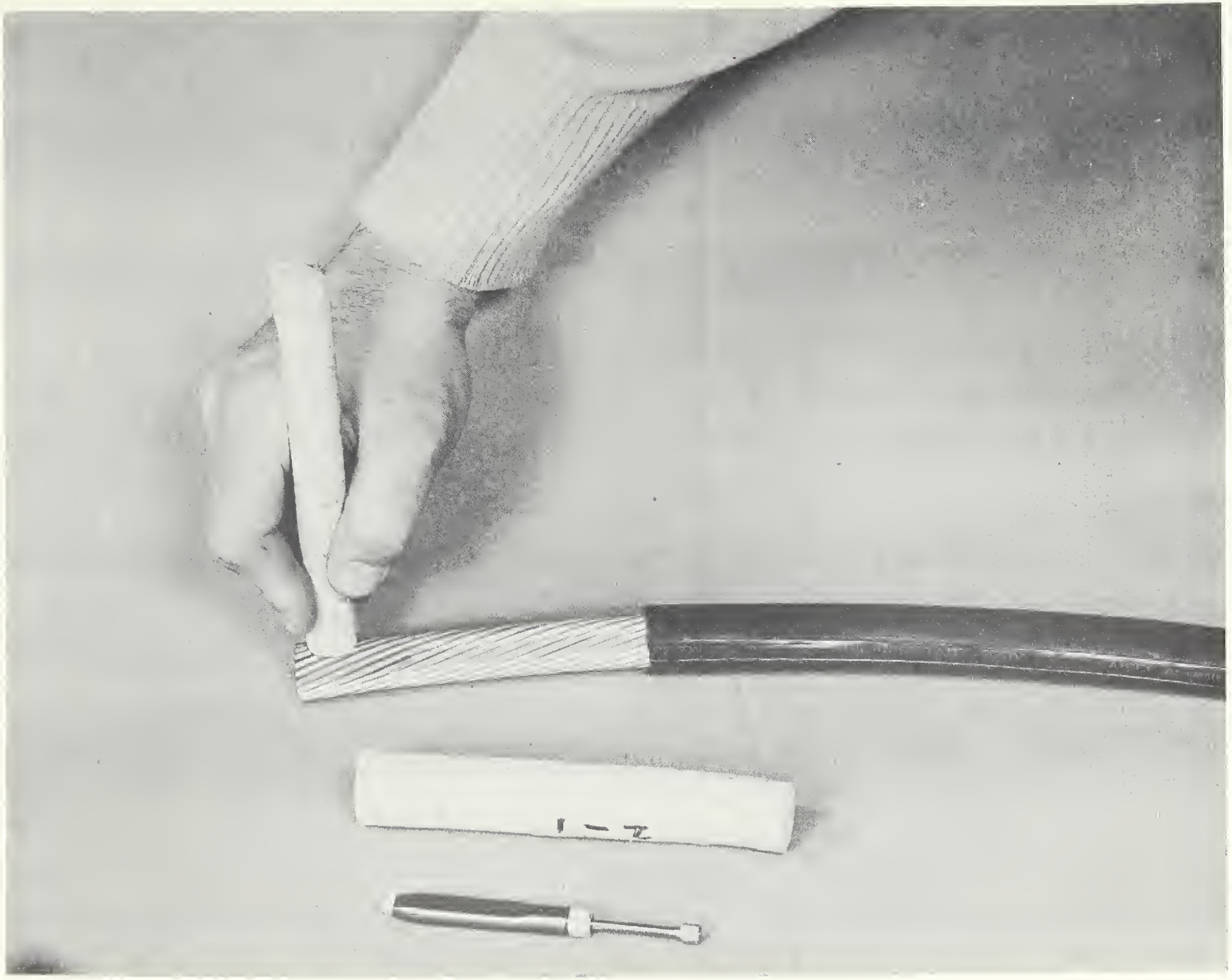

Figure 19

Using a Glass Fiber Brush to Remove Oxide from Aluminum Conductor Strands Prior to Connection